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Boeing Helicopters Advanced Rotorcraft Transmission (ART) Program Summary of Component Tests

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BOEING HELICOPTERS

ADVANCED ROTORCRAFT TRANSMISSION (ART) PROGRAM

SUMMARY OF COMPONENT TESTS

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ABSTRACT

On May 20, 1988, Boeing Helicopters was awarded a contract by the U.S. Army Aviation Systems Command (AVSCOM) and the NASA Lewis Research Center to conduct the Advanced Rotorcraft Transmission (ART) program. The ART program is structured to incorporate key emerging material and component technologies into an advanced rotorcraft transmission with the intention of making significant improvements in the state-of-the-art (SOA). The objectives of the ART program are:

(1) Reduce transmission weight by 25% relative to SOA trends (currently in the range of 0.40 lb/hp).

(2) Reduce transmission noise by 10 dB relative to SOA.

(3) Improve transmission life and reliability, while extending Mean Time Between Removal (MTBR) to 5000 hours.

The ART contract required Boeing Helicopters to select a baseline transmission design that was representative of SOA drive train production technology and then compare this design with an advanced configuration developed during the ART program. Boeing Helicopters selected a transmission sized for the Tactical Tilt Rotor (TTR) aircraft which meets the Future Air Attack vehicle (FAAV) requirements.

Component development testing was conducted to evaluate the high risk concepts prior to finalizing the advanced transmission configuration. A total of eight advanced technology component tests were conducted:

- Noise reduction by active cancellation
- Hybrid bidirectional tapered roller bearings
- Improved bearing life theory and friction tests
- Transmission lube study with hybrid bearings
- Precision near-net-shape forged spur gears
- High profile contact ratio noninvolute tooth form spur gears

- Parallel axis gear noise study

- Surface modified titanium accessory spur gears

This paper summarizes the results of the eight component tests conducted under the ART contract.

INTRODUCTION

The ART program is viewed as a means of providing the rotorcraft industry with a unique opportunity to advance the technology base for rotorcraft drive system via a path similar to that traditionally followed in engine development.

The ART program is structured in two phases. The first phase involves four contracts and is the preliminary design and component validation phase. This phase allows each contractor to develop advanced design concepts which incorporate key advanced technologies required to meet the ART program objectives. Trade-off studies and component test and evaluations were conducted to support each design concept. The results of the component tests and evaluations have been mostly completed and their test results will be reported in this paper. The second phase of the ART program will involve the selection of one or two contractors to conduct a full scale demonstrator program.

BACKGROUND

The Advanced Rotorcraft Transmission (ART) program is a U.S. Army funded, joint Army/NASA program to develop and demonstrate lightweight, quiet, durable drive train systems for the next generation rotorcraft. This program allows the participants, which include Bell Helicopter Textron, Inc., Boeing Helicopters, McDonnell Douglas Helicopter and Sikorsky, to evaluate key emerging material and component technologies and novel design concepts for advancing the technology of future rotorcraft transmissions. The specific objectives of ART include the reduction of drive train weight by 25 percent, a reduction of noise level at the transmission source by 10 dB and the attainment of at least a 5000 hour MTBR drive system.

The ART program requires each participant to select a vehicle fitting into one of the two distinct next generation aircraft classes, and to demonstrate their proposed advanced concept drive trains. The two classes of aircraft are:

(1) Future Air Attack Vehicle (FAAV) - A 10,000 to 20,000 pound aircraft capable of undertaking tactical support and air-to-air missions.

(2) Advanced Cargo Aircraft (ACA) - A 60,000 to 80,000 pound aircraft capable of heavy lift field support operations.

AIRCRAFT SELECTION

Boeing Helicopters selected a Tactical Tilt Rotor (TTR) aircraft which met the requirements outlined for the FAAV (nominal gross weight of 10,000 to 20,000 pounds).

The TTR aircraft shown in Figure 1 is a small lightweight attack tilt rotor aircraft designed to be highly maneuverable and survivable. It is also applicable to counter-air-attack and air-to-air combat missions. Its primary mission gross weight is about 17,223 pounds.

In general, the TTR drive system arrangement is similar to that of the V-22 Osprey aircraft. It is a twin engine configuration with one engine mounted in each wing tip nacelle. The engines pivot with the rotors to convert between helicopter and airplane modes as on the V-22 aircraft. The engine size is in the 2400 SHP class. A candidate engine for this size was a growth derivative of the T700-701C.

Some additional vehicle characteristics pertinent to the ART effort are given in Table 1. Interconnect cross shafting is also required between the rotors and engines so that one engine may drive both rotors in the event of an engine failure. The transmissions will be designed to provide for 30 minutes of operation after lube loss or gear/shaft damage. In general all subsystems of the TTR will provide both crashworthy and damage tolerant characteristics.

The work completed during the early stages of this contract was reported in Reference 1. This work included the various trade studies and selection criteria for the ART drive system. The effect on aircraft performance and cost was also presented in this reference.

COMPONENT DEVELOPMENT TESTING

To achieve the objectives of the ART program, Boeing Helicopters identified eight advanced technology components which require evaluation prior to incorporation into the ART drive system. These new technology materials and components were considered essential in achieving the reduction in weight and noise and the increase in MTBR which are projected when these materials and components are incorporated into the transmission design. The following sections describe the eight component development programs and provide a summary of their test results which were conducted by Boeing Helicopters as part of the ART program. These advanced technology component test programs are as follows:

(1) Noise reduction by active force cancellation

(2) Hybrid bidirectional tapered roller bearings

(3) Improved bearing technology

(4) Transmission minimum lube study with hybrid bearings

(5) Precision near-net-shape forged spur gears

(6) High profile contact ratio noninvolute tooth form spur gears

(7) Parallel axis gear noise study

(8) Surface modified titanium accessory spur gears

1. Noise Reduction by Active Force Cancellation

To achieve a 10 dB reduction in transmission noise, a new concept called Active Noise Cancellation (ANC) was evaluated. This concept uses electronically generated sound to cancel unwanted noise. The principles of constructive and destructive interference form the scientific basis for the process. The noise and vibration produced by a helicopter transmission generally is periodic or repetitive in nature. A microprocessor analyzes the noise or vibration wave form and produces an anti-noise wave form which is exactly 180 degrees out of phase. This concept is illustrated in Figure 2. The microprocessor compares how well the anti-noise wave form cancels the noise and makes corrections after each cycle. Boeing Helicopters worked with Noise Cancellation Technologies on this project.

This work proceeded in two phases. The first phase demonstrated that the concept should work in the frequency range of noise and vibrations produced by a typical helicopter transmission. The initial testing was conducted using a small planetary gearbox which produced planetary frequencies and sidebands in the 1700 Hz range. Examples of typical uncanceled and canceled noise data are shown in Figure 3. Based upon these preliminary tests, noise reductions of 10 dB or greater were achieved. The next phase of this program conducted similar testing using a full scale helicopter transmission. A CH-47 forward transmission test was

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conducted in an acoustic chamber, as shown in Figure 4, to determine the effectiveness of Active Noise Cancellation for achieving a significant reduction in noise and vibration being produced by a full scale helicopter transmission. Although this test was conducted under no load, the vibration and noise levels were representative of the aircraft conditions.

The general arrangement of the active noise cancellation concept with a single channel controller mounted on one leg of the CH-47 forward transmission upper cover is shown in Figure 5. This figure shows the location of the accelerometer and shaft speed pick-up and the feed of this information into the controller. The output from the controller is then input into the shaker which is mounted vertically on the mounting lug. The results of one of these tests is shown in Figure 6. This test again indicated that a significant reduction in the fundamental lower planetary frequency could be achieved on a full scale transmission. Based upon the test results of the active noise program completed to date, Table 2 summarizes some of the significant accomplishments.

In addition to the active control testing, testing is planned to evaluate the decoupling of the CH-47 first stage planetary ring gear as shown in Figure 7, and gear and transmission housing damping using Dayad material placed in critical areas. Hardware for conducting these tests have been completed and testing is currently being done. It is expected that a combination of both active control and damping will be required to achieve the goal of 10 dB or greater reduction in transmission generated noise.

2. Hybrid Bidirectional Tapered Roller Bearing

The selected ART drive system makes extensive use of single helical gears. The use of thrust type bearings are required to react the thrust produced by these single helical gears. Boeing Helicopters selected a bidirectional tapered roller bearing to react the thrust and radial load at one end of each shaft. The other end of the shaft was supported by a cylindrical roller bearing that reacts the radial load and allows for axial growth due to loads and thermal growth.

Bidirectional tapered roller bearing have been developed by the Timken Company for use in turbine engines to react only thrust loads. The design concept has been expanded for use in the ART transmission to react both radial and thrust loads and the basic concept is illustrated in Figure 8. This type of bearing offers high load and speed capability within a single row bearing and can also react combined thrust and radial loads produced by the gear reaction in two directions. In addition, the problems of preloading a set of tapered roller bearings and varying preload setting due to thermal growth will be eliminated by this concept. As shown in Figure 8, an initial bearing setting is provided by the bearing manufacturer much like that of unmounted radial clearance for ball and roller bearings. The proposed bearing design was also tested as a hybrid which incorporates the use of ceramic rollers and poly-ether-ether-ketone (PEEK) composite cages to reduce dynamic loads, increase performance under marginal or oil-off operation and increase the fatigue life of this type bearing.

The Timken Company conducted the design, fabrication and test of these bearings. A variety of material combinations (CBS 600 steel, silicon nitride, zirconia and PEEK) were evaluated during this test program to determine the optimum design to meet the overall objectives. Typical components for the bidirectional bearing are shown in Figure 9. These components were tested over a wide range of

operating conditions as defined in Table 3. Testing included speeds in excess of 25,000 RPM, rapid and slow load reversal cycles, various oil flow rates, overload, and endurance testing. The results of all of these tests are too extensive to include in this paper, but in summary, all test objectives were achieved and these tests indicated that this bearing concept could be used in the ART transmission.

Figure 10 illustrates typical temperature plots of the cup temperature as a function of speed and oil flow. The goal of this program was to maintain a cup temperature of less than 400^0 F under all operating conditions. Even at the high speed condition of 23,000 RPM and 100% load (3300 LBS radial and 2020 LBS thrust), an oil flow of only 2.5 PTS/MIN was needed to maintain the cup temperature of less than 360^0 F. At the lower speed of 12,000 RPM, a flow of only .5 PTS/MIN resulted in a cup temperature of 280^0 F.

In addition to running with oil, several tests were conducted under oil off operation. Using a hybrid bearing design, one test conducted at 12,000 RPM and 60% of maximum load, ran for one hour without oil and did not fail. The temperature data for this test is shown in Figure 11. After one hour without oil, the oil flow was turned on and the bearing returned to normal operating conditions. A similar bearing made from all steel components and operating under similar conditions ran for approximately 20 minutes and failed. This test indicates that the hybrid bearing design offers significant advantages when operating under oil off conditions.

Finally, endurance testing was conducted on the hybrid bearing design and the test data demonstrated a life improvement of approximately 12 times that of a standard steel bearing configuration.

3. Improved Bearing Technology

Significant improvements in bearing technology are required to achieve the goals of weight reduction and increased MTBR's as demanded by the ART program. The work planned for this task supplements the work previously completed on developing the bidirectional tapered roller bearing and also includes the following additional work:

(1) Improved life prediction theory (SKF New Life Theory)

(2) Interaction of surfaces of rolling element materials

(3) Optimized design of hybrid ball and roller bearings

Two computer programs, PC-SHABERTH and PC-CYBEAN, were modified by MRC Bearings, SKF Aerospace to incorporate the new bearing life theory and the traction properties of various material combinations to better predict the service life of transmission bearings. With this life model, it was hoped that bearing fatigue lives could be optimized to achieve the desired goal of a 5000 hour MTBF gearbox. The difference between the SKF new life formulation and the most commonly used Lundberg-Palmgren (AFBMA) life formulation is shown in Figure 12. The new theory establishes a fatigue limit stress and a modified stress volume for calculating the bearing life. With this new life formulation, the effects of the following conditions can also be included in the life prediction:

(1) Shear stresses due to traction

(2) Hoop stress due to fit-up and rotation

(3) Residual stresses

(4) Lubricant contamination

Although none of the above factors can be included in the current life

prediction methodology, it is a known fact that all of these factors have a significant effect on the actual life of bearings. This new life theory does provide the capability to better predict bearing lives in future helicopter transmission.

In support of this work, traction tests were performed under stress, temperature, lubrication and surface roughness conditions which simulated those of the ART transmission bearings. All traction tests were performed at a maximum Hertz stress of 294 ksi, which corresponds to the stress of the heaviest loaded roller in a typical helicopter transmission application. A ball on disk traction test rig as shown in Figure 13 was used to conduct these tests.

Based upon the materials selected for the ART transmission, the material combinations shown in Table 4 were selected for conducting the traction tests.

The ball specimens used in the traction testing were fabricated from 13/16 inch diameter M-50 Grade 10 balls and similar geometry silicon nitride balls were made of Norton NBD-100 material. The disk test specimens had an outside diameter of 3.75 inches and a thickness of 0.5 inches. The surface finishes of the disk test specimens were measured to be less than 4 micro-inches. The ball test specimens had measured surface finishes less than 0.5 micro-inches.

The traction tests were run at a rolling speed (disk peripheral velocity) of 250 inches/sec. The temperature of the chamber enclosing the ball and disk was controlled to produce a range of lambda (film thickness/composite surface roughness) values representative of transmission operation. The lambda values calculated for the ball-on-disk test rig at various traction test temperatures are summarized in Table 5.

Tests were conducted using lubricants meeting the MIL-L-23699 and DOD-L-85734 specifications. The lubricants were dripped fed onto the disk near the ball/disk contact at the rate of approximately one drop per second. This oil drip rate was found to provide ample lubrication at the ball/disk contact resulting in full EHD film formation.

Table 6 summarizes the maximum friction coefficients for 29 traction tests performed for the various material combinations evaluated under common test conditions. In nearly all cases tested, the traction coefficients decreased with increasing temperature. The trend of decreasing friction coefficient with increasing temperature was not anticipated prior to actual testing. It was expected that as the temperature increased, the EHD film thickness would decrease resulting in lower lambda values and consequently more surface asperity contact and higher friction coefficient. However, since this same trend has been observed in other lubricant tests, it is believed that this effect is real.

In the lubricated tests, the lowest maximum friction coefficient measured was 0.021 for the ceramic ball/M50 NiL disk combination at 400^{0}F. Of the three disk materials tested, M50 NiL produced the lowest friction coefficient in all but one test case. In general, the friction coefficients measured for the three disk materials were lower with the ceramic ball than the M50 ball. The following conclusions and observations were made based on the traction test results:

(1) M50 NiL provided the lowest friction of the three disk materials tested.

(2) The friction coefficients were generally lower with the ceramic ball than with the M50 ball.

(3) At very high lambda's (10), the lubricated traction curves were virtually identical for all material combination tested.

(4) Friction coefficients generally decreased with increasing temperature in spite of the lower calculated lambda values.

(5) In unlubricated tests, the peak friction coefficients were an order of magnitude higher than those observed with oil lubrication.

(6) M50 NiL provided the lowest unlubricated friction followed in turn by TDC coated M50 and VASCO-X2.

The above data was then incorporated into the computer programs and then used to improve the life prediction of bearings and also to optimize the design of a hybrid roller bearing for use in the CH-47 engine transmission. This bearing and two additional hybrid bearings (ball thrust and cylindrical roller) were then tested in the next component test plan.

4. Transmission Minimum Lube Study with Hybrid Bearings

Hybrid (ceramic) rolling element bearings have the potential to offer significant improvement in bearing performance for future transmissions. These benefits include longer fatigue life, good marginal lube performance and reduced weight (approximately 22% per bearing). Also, significant reduction in centrifugal rolling element loads can occur by just changing from steel to ceramic. For very high speed bearings, this can result in a significant improvement in bearing fatigue life.

The main reasons for using hybrid bearings in the ART transmission was primarily to take advantage of the potential of operating these bearings at reduced oil flow rates and therefore reducing the lubrication system weight. Boeing Helicopters tested the hybrid bearing concept in a CH-47 engine transmission and compared these results with standard bearing operation. Extensive testing was conducted to evaluate the hybrid bearings over a wide range of operating conditions. Included in these tests was the reduction in oil supply, the use of three types of lubricants with different oil viscosities and the determination of heat generation rates. Hybrid bearing test results indicate that good marginal lube performance and reduced friction can be achieved. Figures 14 and 15 show temperature data for both hybrid ball and roller bearings as compared to standard steel bearings for three different lubricant and at various loads. Generally, the hybrid bearings operated at lower temperatures except for the very low load conditions. Under these very low loads, hybrid bearings appear to have higher skidding which could result in the slightly higher temperatures. Similar tests were conducted for reduced oil flow rates and resulted in similar data. These tests indicated that a reduction in the lubrication flow rates to all bearings is achievable when using hybrid bearing designs. In combination with lighter weight, longer fatigue life and corrosion resistance, it is expected that the use of hybrid bearings can make a significant impact toward achieving the design goals of the ART transmission.

5. Precision Net Forged Spur Gears

Precision, near-net-shape forging of helicopter gears offers several advantages in the design of Advanced Rotorcraft Transmissions because this process has shown the potential for:

(1) Reducing machining, material and energy requirements

(2) Increasing fatigue life

(3) Improving the tooth bending endurance limit.

These potential benefits are expected to contribute directly to reducing weight and extending service life of the ART gears.

The key to successful precision forging is the design and manufacture of the forging dies to precise dimensions. Corrections must be built into the forging dies to accommodate the distortions and thermal changes which occur during the forging process. The process developed by the EATON Corporation results in the final forged gear being within several thousandths of an inch of the predicted value. This process produces a forged gear blank that is equivalent to a rough machined gear prior to final grind. This is achieved without any machining and could be a significant cost reduction in the machining cost of helicopter gears.

When gears are manufactured from conventional forged blanks, the gear teeth are actually cut into and across the forging flow lines. This does not provide for any material grain orientation along the tooth profile and root radius. Conversely, when a gear blank is near net shape forged (see Figure 16), the rough shape of the gear teeth are produced in the forging operation. Therefore, the material grain flow is around the contour of the gear teeth themselves, as shown in Figure 16. It is this conformity of the forging flow lines which should provide for the improvement in fatigue characteristics, most notably in bending but also in surface fatigue.

The approach for achieving the objective of this task was to develop, design, and manufacture tooling compatible with the standard Boeing Helicopters single tooth fatigue test gears, manufacture a representative batch of test gears, inspect the geometry and metallurgy of the gears, and test their bending fatigue load capacity relative to the capacity of similar, conventionally manufactured gears. The Eaton Corporation designed the dies and forged the test gear blanks made from VASCO-X2M steel. In addition, a batch of test gears was manufactured from an advanced VASCO steel with a Nickel additive for improved fracture toughness and basic load capacity. A large data base from prior testing of standard test gears was available and provided a good statistical comparison.

Single tooth bending fatigue tests were conducted to determine if the net forged gears had higher bending stress limits. The test was conducted on conventional VASCO-X2M steel gears made by the standard machining process and compared against two net forged gears made from two types of VASCO-X2M steel. The results of this testing are summarized in Figure 17. Also included in this figure is data for conventional 9310 steel gears. The data shows that the bending stress limit of the net forged VASCO-X2M steel gear was slightly higher than that of the conventional VASCO-X2M steel gear which was used as the baseline for this testing. Although the bending stress was slightly higher (approximately 6%), the data did not show a significant difference to assure that a change in bending stress limit could be used in future design made from the net forged process. The second net forged gear specimens (made from VASCO-X2M + Ni steel) showed no difference in bending stress. This testing did prove that the net forged process could be used without any negative effect on the bending properties and still take advantage of the net forged process for manufacturing cost reduction. When compared to the standard 9310 steel gears, a significant increase in bending stress was achieved for all versions of the VASCO-X2M steel gears. The bending stress was increased by 50,000 PSI or an approximate increase of 20% was achieved. This type of increase can make a significant difference in gear sizing for achieving the same power limits.

6. High Profile Contact Ratio Noninvolute Tooth Form Spur Gears

The objective of this task was to design, build, and test a set of spur gears which utilized high profile contact ratio noninvolute tooth form (HCR-NIF) to provide a relatively constant curvature radius along the tooth profile while yielding a profile contact ratio of at least 2.1. This configuration allows the use of a high reduction ratio in a single stage while simultaneously minimizing noise generation and improving surface load capacity. The High Profile Contact Ratio (HCR) provides a reduction in the loading on any single tooth through improved load sharing. By extending the length of the gear teeth and changing the tooth proportions and pressure angle, the total transmitted tooth load is shared among alternate two and three pair contact conditions.

Unfortunately, the extended contact associated with HCR involute gears also results in higher sliding velocities and lower relative curvature radii at the extremes of contact thus reducing both the scoring resistance and surface durability of the gears. This effect is largely counteracted by the improved load sharing and thus some net benefit in load capacity is obtained. The addition of the Noninvolute Tooth Form (NIF) tends to improve the relative curvature radii at the extremes of contact and thus further enhance the load capacity of the gear set while retaining the noise level improvements.

A test program was conducted to investigate the performance of High Profile Contact Ratio - Noninvolute Form gearing, the relative noise characteristics, and load capacity. A set of conventional, standard contact ratio gears of the same reduction ratio and center distance was used for comparison.

Two sets of spur gears were designed for a 10 inch center distance Gear Research Test Rig in the overhung configuration. One set of gears was designed for standard involute tooth form and proportions while the second utilized the High Contact Ratio - Noninvolute Tooth Form (HCR-NIF). The gears were designed for a 1.75:1 ratio and had a diametral pitch of 4.55 and were fabricated from VASCO-X2M steel. The pinion speed for this test was 2400 RPM. Testing of these gears have not been completed at the time of this paper and therefore the final effects of this gear configuration has not been determined at this time.

7. Parallel Axis Gear Noise Study

The problem of gear noise in helicopter transmissions is ever present. The main exciting forces which produce the noise are the gear teeth meshing forces. While this is an over-simplification, since many factors influence transmission noise in addition to the gear mesh forces, the simple fact remains that if the basic gear tooth exciting forces are reduced and the amplifying factors remain constant, then the overall noise level of the transmission system will be reduced.

Among the several ways in which the gear tooth meshing forces may be reduced, two of the most directly applicable to helicopter transmissions are the form of the teeth and the overall contact ratio. Both approaches are attractive for an aerospace application since, unlike other "treatment" methods, which are applied with penalties to either system weight or performance, these approaches have the potential for reducing noise without causing any increase in overall system weight or reducing performance. In fact, both approaches also offer the possibility of actually providing improved gear performance in terms of longer life, higher load capacity, improved reliability, and reduced

weight while simultaneously reducing noise levels.

The objective of this task was to determine, by controlled testing and actual noise measurements, the effect of changes in the profile, face, and modified contact ratios and the gear tooth form, separately and in combination, for spur and helical gears.

The specific gear configurations to be tested are shown in Table 7. While a wide range of specimens is shown, they will all be configured as nearly alike as practical, within the limitations imposed by manufacturing considerations and the test stand. The gears were designed to operate at relatively the same stress levels for the same applied torque.

These test gears are all compatible with and will be tested in the NASA Lewis Noise Test Rigs shown in Figure 18. Testing will be conducted for eight gear configurations and two sets of each configuration. A total of 16 gear sets of data points will be recorded and compared for noise levels. The test conditions for these tests are shown in Table 8. Test will be conducted at three speeds and three torque conditions and each data point will be repeated approximately five times to insure a 95% confidence limit of +/- 1 dB. This close tolerance on dB variation at each data point is required to insure that differences between gear sets and assemblies can be measured and compared.

Acoustic intensity, vibration and sound pressure measurements will be taken at each data point. Acoustic intensity will be measured over a 4 x 5 grid that has been defined on the upper cover of the test gearbox and will be recorded by a robot commanded probe. Accelerometers will be mounted on the bearing end caps in parallel and perpendicular to the line of action. Finally, two microphones will be mounted above the gearbox and will record the sound pressure levels. All data will be recorded in an acoustically treated test room to isolate only the noise produced by the test gear mesh. Typical data recorded for the baseline spur gear test is shown in Figure 19. This figure shows data for three shaft speeds (3000, 4000 and 5000 RPM) over the frequency range of 1000 to 7000 kHz.

8. Surface Modified Titanium Accessory Spur Gears

Accessory gears in many helicopter applications, especially for high power aircraft, are sized more by geometric requirements than by load capacity. In general, the pitch diameters of such accessory gears are determined by the restraints imposed by the overall design of the gear box. Therefore, as the basic gearbox becomes larger, the accessory gears are often designed with very small face/diameter ratios and are heavier than required to transmit the power required by the individual accessories. Since there are practical manufacturing limits on how small the face width can be on a large diameter gear, such gears are often weight inefficient. One way of reducing the weight of these gears would be to use a material which has a lower density than the steel typically used.

Titanium is one such material, however, it has not gained wide spread use because it performs poorly in dynamic, frictional applications. Titanium gear teeth suffer from a rapid galling type failure, despite using a good lubricant. Recent advances in surface modification processes, such as ion implantation, may make it possible to treat the surface of titanium gears to minimize the galling problem. If this approach is successful, a definite weight advantage can be obtained. Thus the objective of this task is to design, build, and test two sets of spur gears which utilize two different surface modified titanium as the gear material.

The test program is aimed at investigating the performance of surface modified Accessory gears. Particular items of interest are relative scoring and surface durability capacities of titanium gears compared to a set of conventional steel gears at the same reduction ratio and center distance.

Two sets of spur gears were designed to operate on the 6 inch center distance Boeing Helicopters Gear Research Test Rig in the overhung configuration. One set of gears was designed for durability testing while the second set was designed for scoring testing. The durability test gears are a 1.67:1 ratio set while the scoring test gears are a 1:1 ratio set.

The gears were manufactured from Ti-6Al-4V Titanium Alloy in accordance with the contractor's normal practice so that they are fully representative of actual aircraft gears. However, the gear tooth profiles were surface modified by two candidate processes in an effort to avoid the galling problems which have thus far limited the application of Titanium gears in power systems.

The test results of the initial titanium pinion running against a titanium gear indicated generally poor scoring resistance for the two surface modification treatments at the planned test conditions. These gears failed at very low torque levels in the range of less than 10% of the scoring load capacity of equivalent steel gears. The failure mode was very severe scoring and galling of the tooth surface. The test conditions were modified and a titanium gear was run against a standard steel pinion at lower speed and oil temperature. These gears failed at higher torques levels compared to the titanium/titanium gears but still only in the range of 20% to 50% that of the scoring load capacity of the equivalent steel gear configuration. The failure mode changed from severe scoring to excessive smooth surface wear of the titanium gear. The steel pinion showed no signs of distress. The results of these tests at the various test conditions are summarized in Figure 20.

Surface durability testing was also conducted on the same type of surface modified titanium gears and the results were very similar. When running a titanium against a titanium gear, failures were recorded at very low torque levels. Values of less than 10% of the surface durability capacity of equivalent steel gears was achieved. Failure was due to excessive wear and torque drop off in the closed torque system. The test condition were again modified to run a steel pinion against a titanium gear with only slight improvement and higher torque levels. A stabilized torque condition (no wear with time) occurred at a torque of approximately 10% to 15% of the surface durability load capacity of equivalent steel gear set. At higher torque levels, excessive wear of the titanium gear was measured and torque drop off was measured in the closed loop system. In all cases, no distress was noted on the steel pinion. The results of this series of test are summarized in Figure 21. Note the break in the torque and torque drop scales on this figure.

The results of these tests did not provide the confidence to use titanium accessory gears in the ART transmission design. Both the scoring and surface durability were too low for consideration in this application. More work will have to be done to investigate other surface treatments to increase the load capacity of titanium gears to insure their use in future accessory gear type application.

SUMMARY

Work conducted by Boeing Helicopters under the Advanced Rotorcraft Transmission (ART) Technology Integrated Demonstration program has provided significant advancements in

the state-of-the-art for future rotorcraft drive systems. This type of work has been much needed to keep pace with the design goals of future aircraft drive systems. Significant reduction in drive system weight and noise and increases in the MTBR's have been demonstrated during this program. Design studies completed by Boeing Helicopters indicate that all of the ART goals can be achieved through the use of novel designs and advanced technology components. Eight advanced technology material and component tests were evaluated during this program. Most component tests provided the confidence that these high risk developments would meet the requirement of the ART program goals. The titanium accessory gear test was not successful and two tests that were not completed at the writing of this paper are still being evaluated.

ACKNOWLEDGEMENT

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Table 1. Baseline Aircraft Parameters

Primary Mission Gross Weight, Lbs	17,223	
Structural Design Gross Weight, Lbs	16,155	
Wing Span, Ft	36.2	
Wing Area, Ft^2	224	
Wing Loading @ SDGW, PSF	72	
Rotor Diameter, Ft	25	
Disc Loading @ PMGW, PSF	17.5	
Number of Blades Per Rotor	3	
Rotor Solidity	0.117	
Engines	Two GE 700-701C	
Maximum Power SLS Installed, SHP	2019 (Each)	
Condition:	**Cruise**	**Hover**
Output Shaft Power Rating, HP	1955	2444
Transmission Input Rating (AEO), HP	1939	2424
Mast Output Torque, Ft-Lb	21,396	21,396
Main Rotor Speed, RPM	480	600

Table 2. Active Control Accomplishments	
OBJECTIVES	**RESULTS**
• **Develop Controller Software** - High frequency, incl sideband - Multiple channels (interacting)	• **Able to Control LP1 Frequency Group** - 1,450 Hz functional + 4 sidebands - 4 x 4 interactive controller
• **Design Control Hardware** - Actuators, feedback systems - Use synch signal from transmission	• **Used Readily Available Components for Test** - Piezoelectric reaction mass shakers - Acceleration feedback sensors - Synchronizing signal from rotor shaft
• **Force Requirements**	• **Estimated & Verified Control Force Requirements**
• **Structure Borne Transmission Noise**	• **Reduced LP1 Group upto 15 dB**

Table 3. Bidirectional Tapered Roller Bearing Test Plan
I. All Steel Bearings Combined radial & thrust loads (3,300 lbs R / 2,020 lbs T) Speed upto 23,000 rpm Flow rates to bearings (0.5 - 3.5 pts/min) Major/minor load sequence (rapid/slow) Overload (125% max) Overspeed (110% max)
II. Hybrid Bearings Combined radial & thrust loads Speed upto 23,000 rpm Flow rates to bearings Major/minor load sequence (same as above) Overload (125% max) Overspeed (110% max) Endurance (>200 hrs)
III. Oil-off All steel bearing Hybrid bearing Speeds 5,400-23,000 rpm Combined radial & thrust loads (60% max)

Table 4. Ball & Disk Test Combinations

BALL	DISK
M50	M50 with Armoloy TDC Coating
M50	M50 NiL
M50	VASCO X2
Silicon Nitride	M50 with Armoloy TDC Coating
Silicon Nitride	M50 NiL
Silicon Nitride	VASCO X2

Table 5. Lambda Values for Ball & Disk Testing	
Temperature °F	LAMBDA
70	9.71
150	2.71
200	1.53
280	0.80
350	0.51
400	0.39

Table 6. Maximum Friction Coefficients				
Temperature	70 °F	70 °F	280 °F	400 °F
Materials (Ball/Disk)	Unlube	Lube	Lube	Lube
M50/M50 + TDC	0.52	0.064	0.046	0.036
M50/M50 NiL	0.50	0.063	0.029	0.022
M50/ VASCO X2	0.55	0.063	0.044	0.045
Si_3N_4/M50 + TDC	0.41	0.064	0.031	0.026
Si_3N_4/M50 NiL	0.40	0.063	0.033	0.021
Si_3N_4/ VASCO X2	0.47	0.063	0.037	0.025

Table 7. Proposed Gear Noise Test Matrix

Test	Contact Ratios			Tooth Form	Type[1]
	Profile	Face	Mod		
Baseline Spur	1.25	0.00	1.25	Involute	S
HCR INV	2.15	0.00	2.15	Involute	S
Baseline Helical	1.25	1.25	1.77	Involute	H
Double Helical	1.25	1.25	1.77	Involute	H
HCR INV	1.25	1.75	2.15	Involute	H
HCR INV	2.15	2.25	3.11	Involute	H
NIF Baseline	1.25	0.00	1.25	Non Involute	S
NIF HCR	2.15	0.00	2.15	Non Involute	S

NOTE: [1] S = Spur, H = Helical

Table 8. Test Conditions for Parallel Axis Gear Noise Study

- **100% Conditions for Pinion**
  - Speed: 5,000 rpm
  - Torque: 2,269 in*lbs
- **Nine Test Conditions**
  - 60% Speed - 60%, 80%, 100% Torque
  - 80% Speed - 60%, 80%, 100% Torque
  - 100% Speed - 60%, 80%, 100% Torque
- **Number of repeat runs established by 95% confidence limit of +/-1 dB**
- **Stabilized operating conditions**
- **Assembly tolerance effect evaluated**

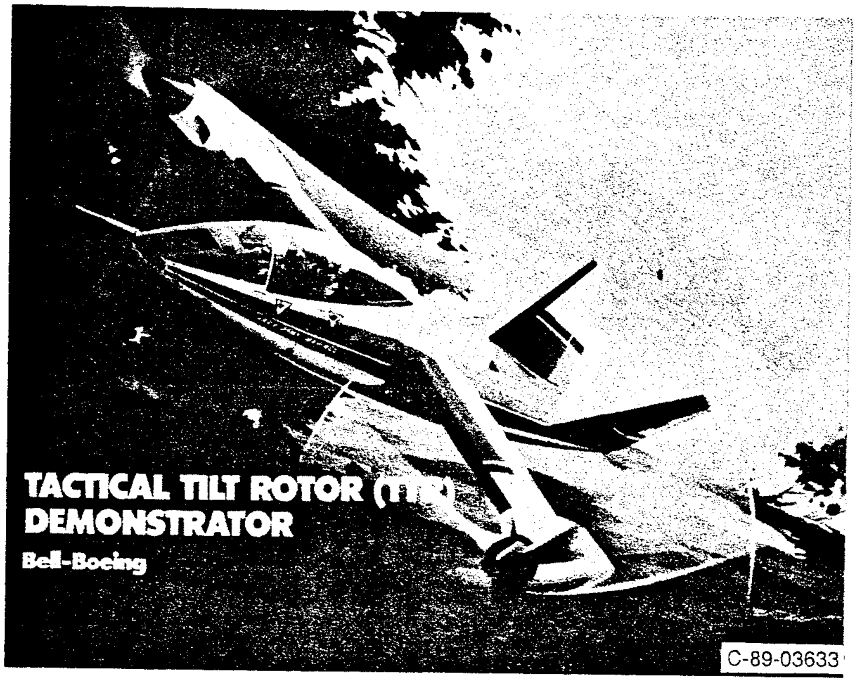


Figure 1. TTR artist's concept.

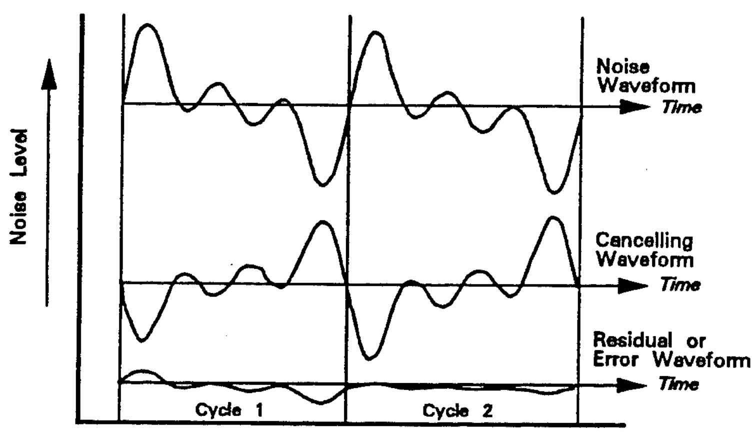


Figure 2. Canceling waveforms.

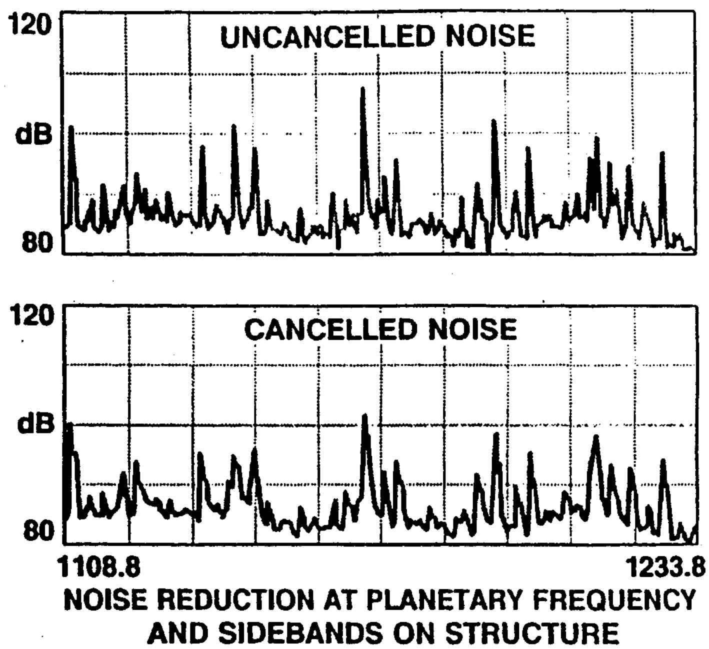


Figure 3. Active noise cancellation on simulated transmission test rig.

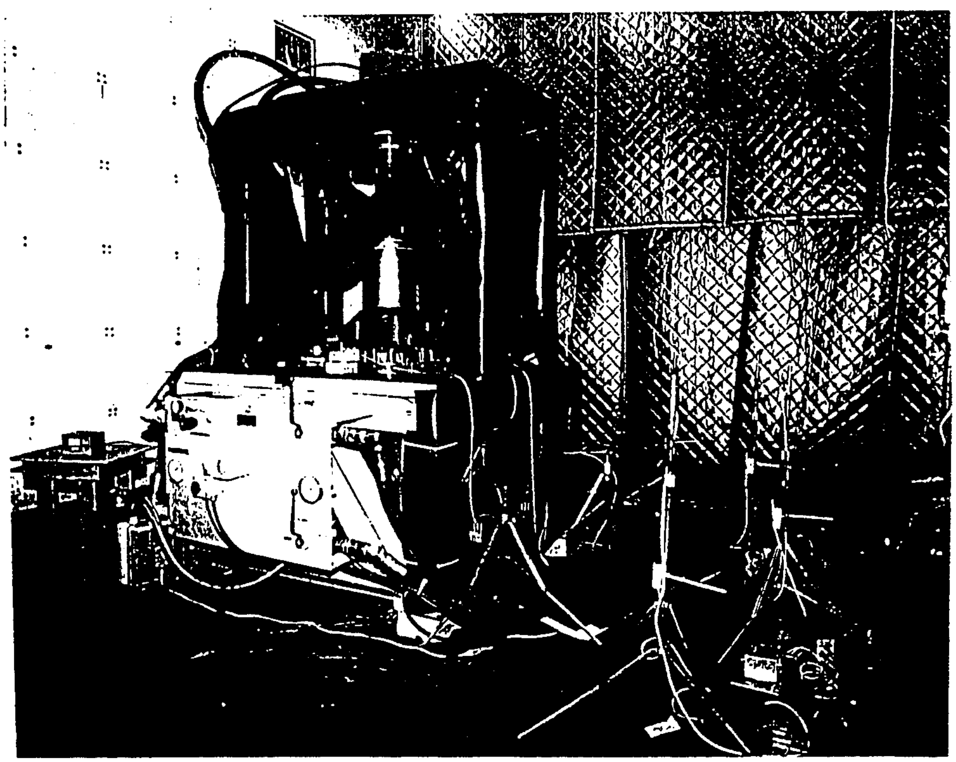


Figure 4. CH-47 forward transmission noise test rig.

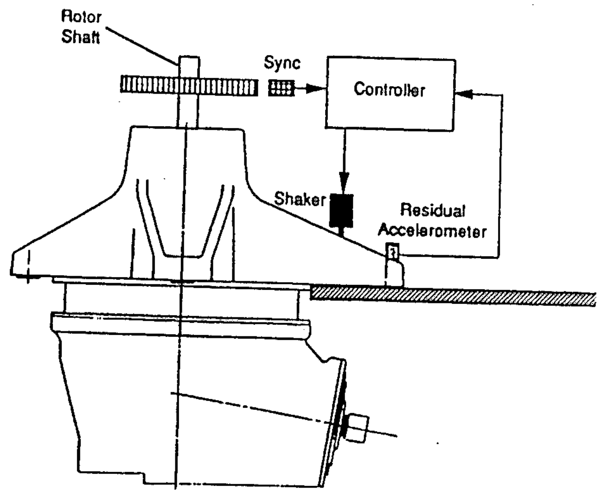


Figure 5. CH-47 active cancellation setup for single channel controller.

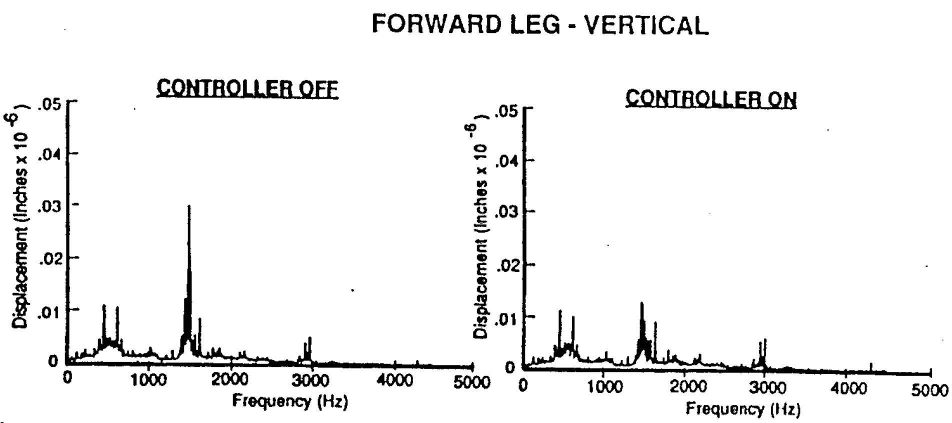


Figure 6. Effect of active control on transmission vibration.

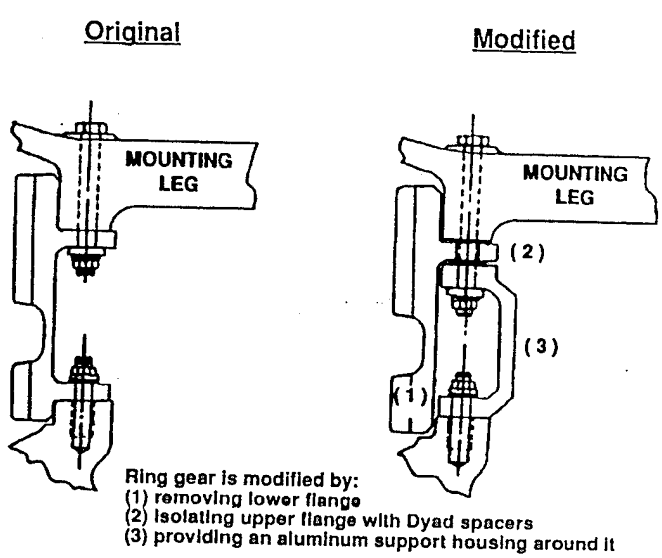


Figure 7. Transmission planetary ring gear modification.

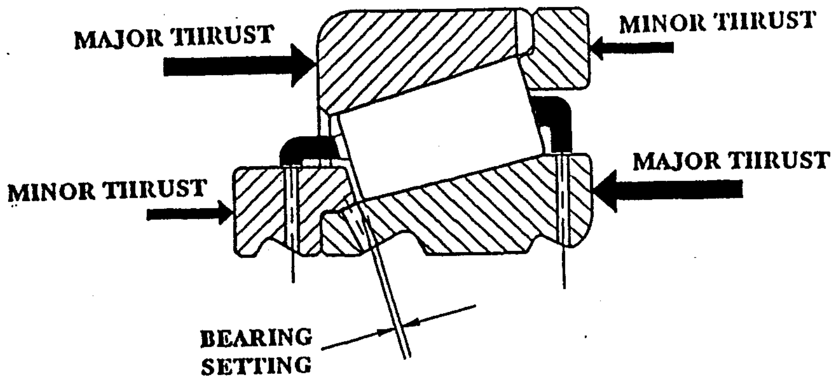


Figure 8. Bidirectional bearing concept.

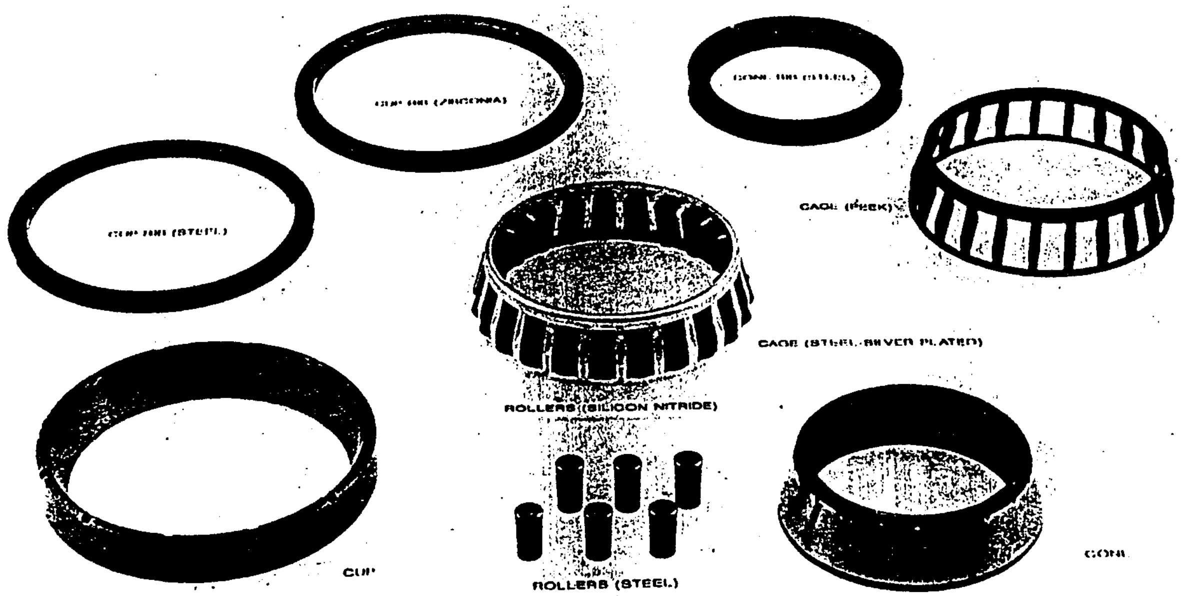


Figure 9. Bidirectional tapered roller bearing test components.

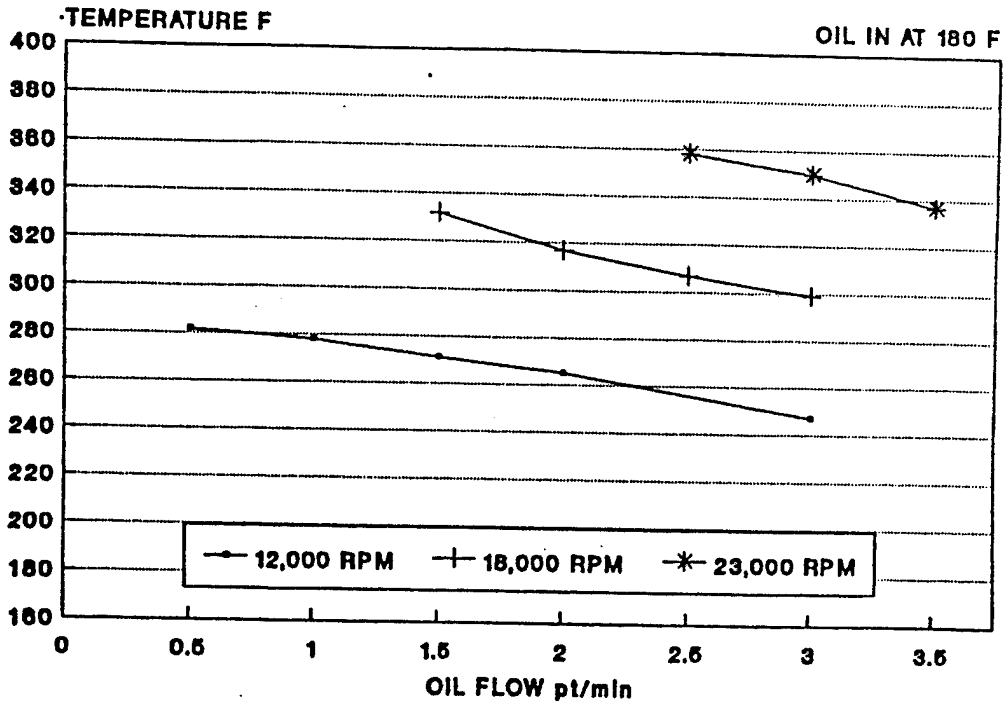


Figure 10. Evaluation of oil flow requirements.

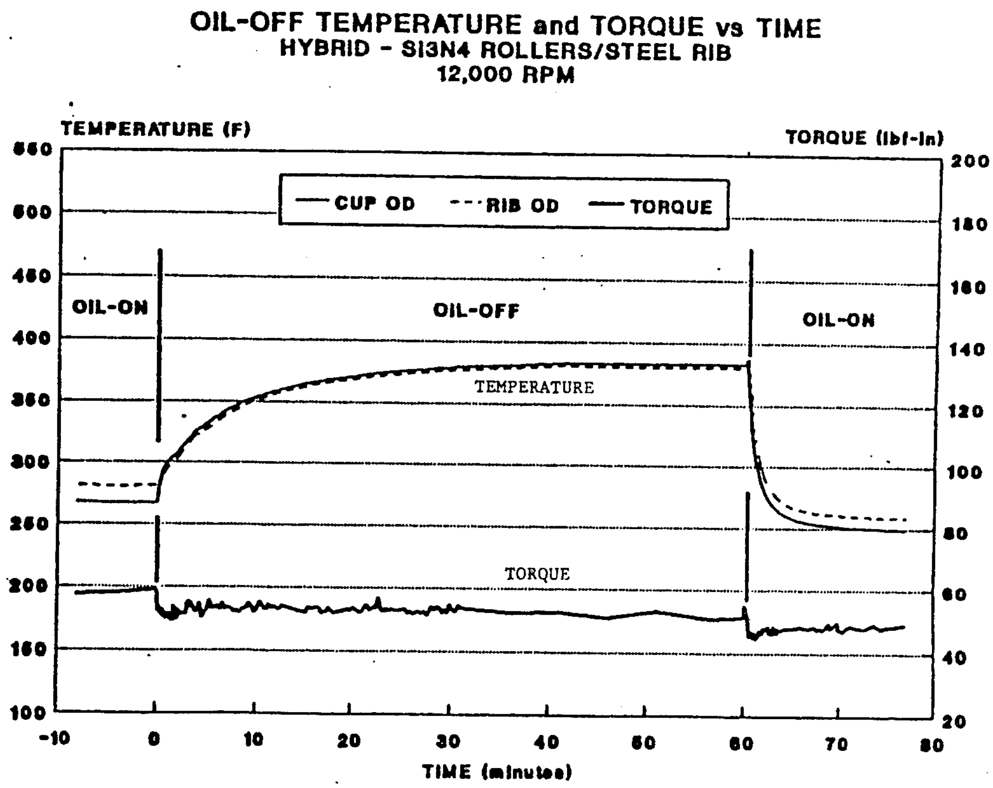


Figure 11. Oil-off test results.

LUNDBERG-PALMGREN (AFBMA) LIFE FORMULATION

$$\ln\frac{1}{S} \sim N^e \tau_0^c \frac{V}{z_0^h}$$

SKF NEW LIFE FORMULATION

$$\ln\frac{1}{\Delta S_i} \sim N^e (\tau_i - \tau_L)^c \left(\frac{\Delta V_i}{z_i^h}\right)$$

WHERE:

$S, \Delta S$ = PROBABILITY OF SURVIVAL
N = NUMBER OF STRESS CYCLES ENDURED
τ_0 = MAXIMUM ORTHOGONAL SHEAR STRESS
τ_L = FATIGUE LIMIT STRESS
V = STRESSED VOLUME
z = DEPTH BELOW CONTACT SURFACE
e, c, h = EMPIRICAL CONSTANTS

Figure 12. Comparison of bearing life equations.

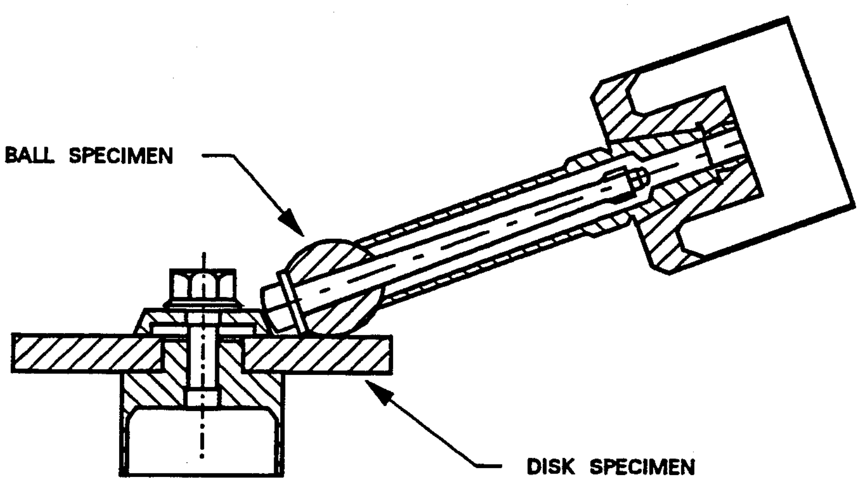


Figure 13. Traction test rig.

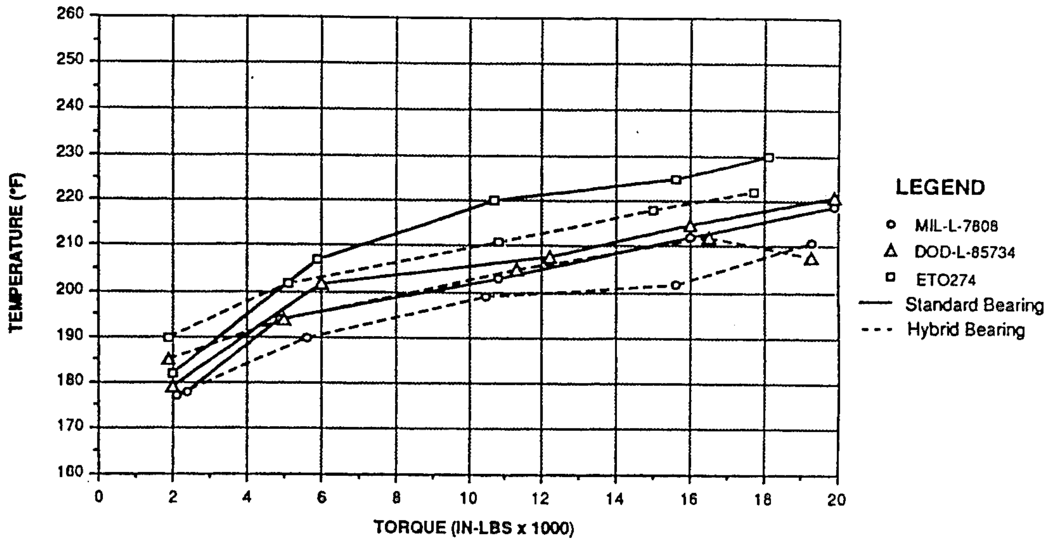


Figure 14. Standard vs. hybrid ball thrust bearing comparison.

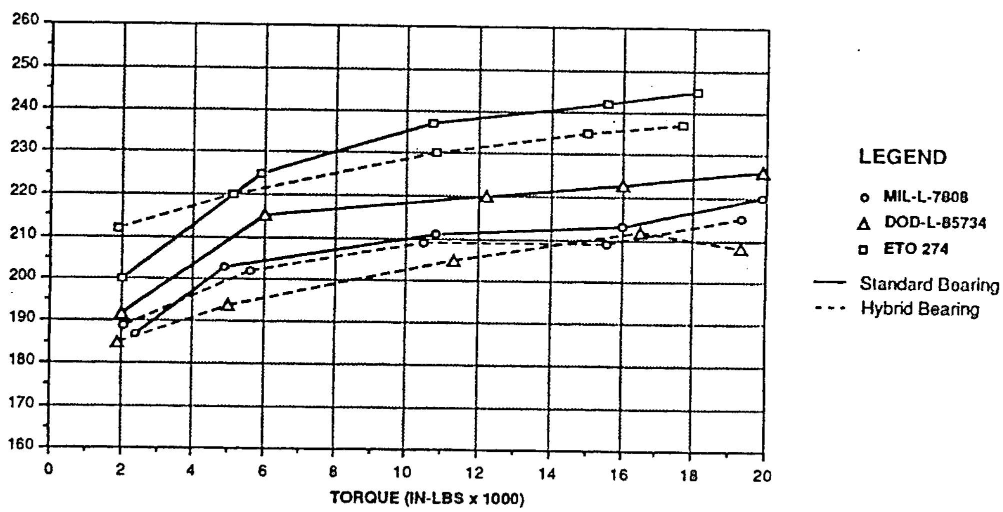
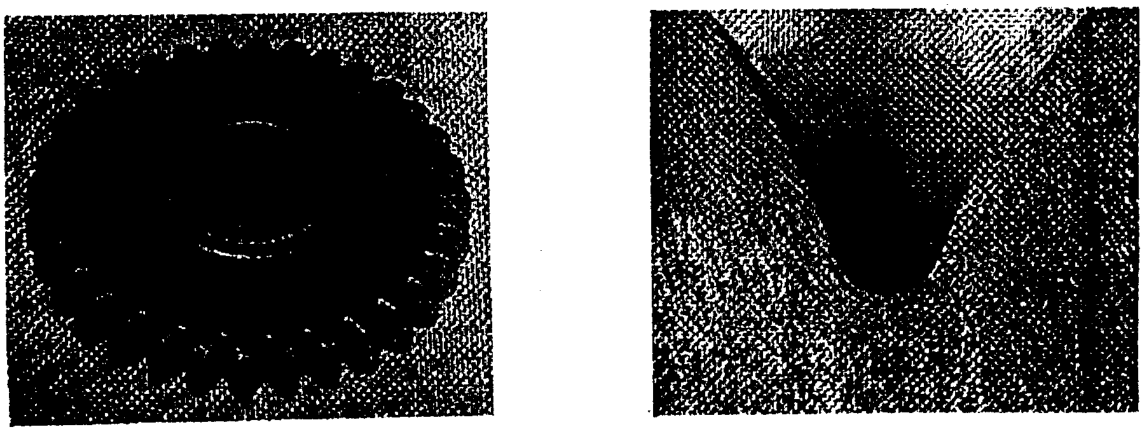


Figure 15. Standard vs. hybrid roller bearing comparison.



NEAR NET SHAPE FORGED GEAR
WITH FORGED TEETH

IMPROVED GRAIN FLOW

Figure 16. Near-net-shape forged gear.

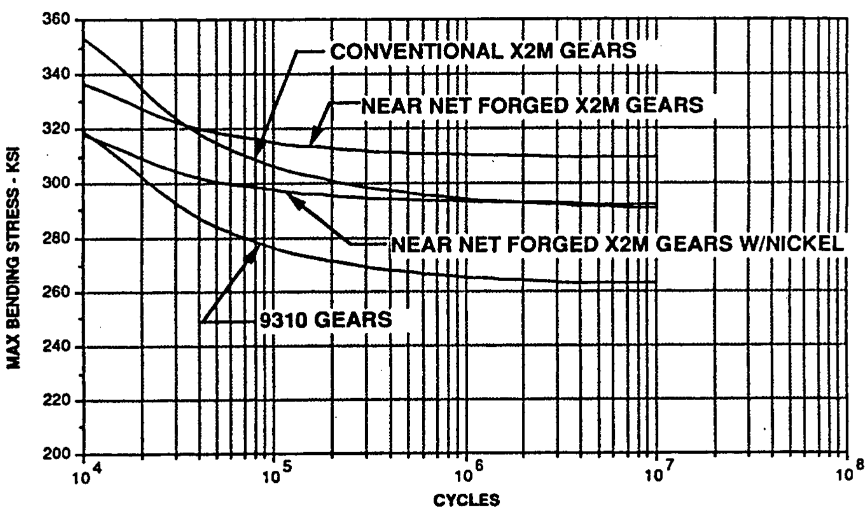
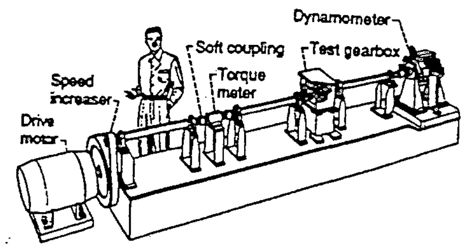
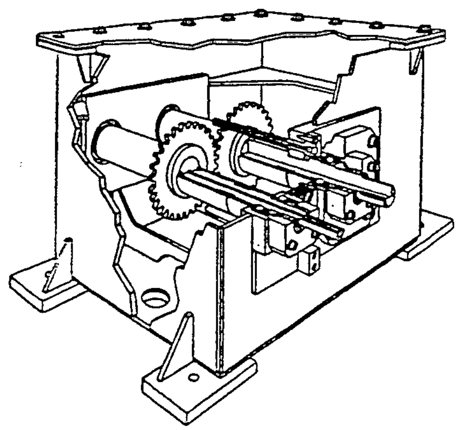


Figure 17. Single tooth bending fatigue test results.



(a) Layout.



(b) Detail of gearbox.

Figure 18. NASA gear noise test rig.

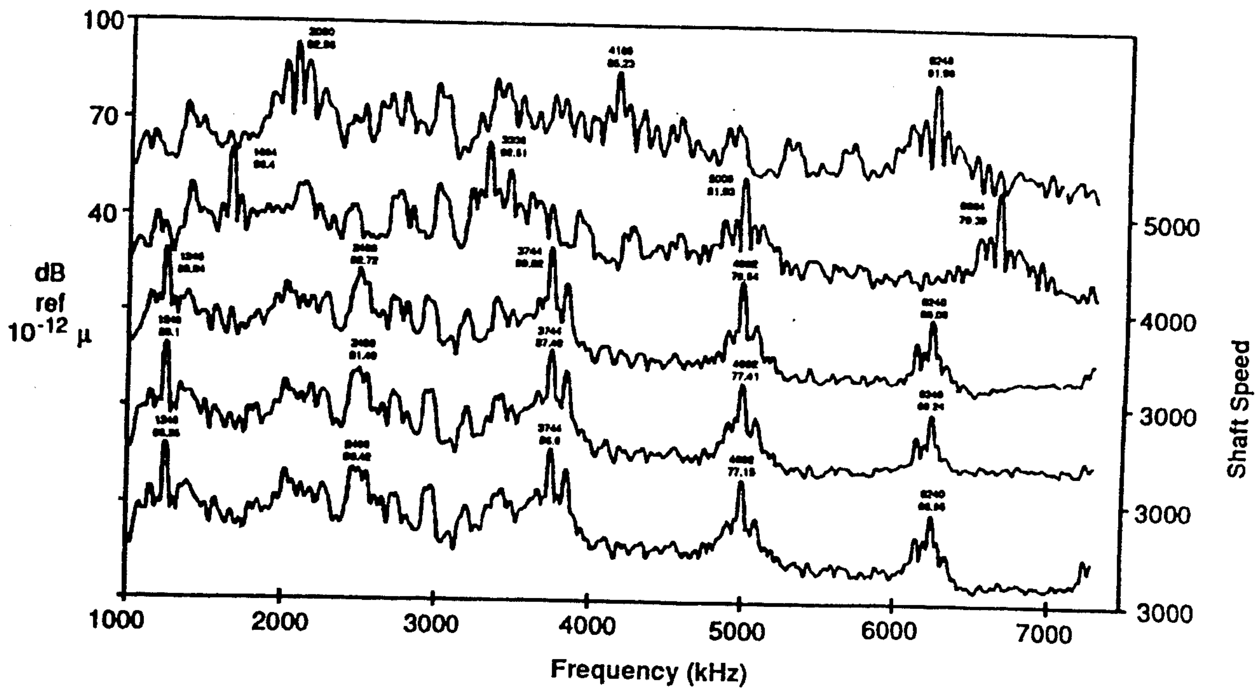


Figure 19. Sound power test data for baseline spur gear.

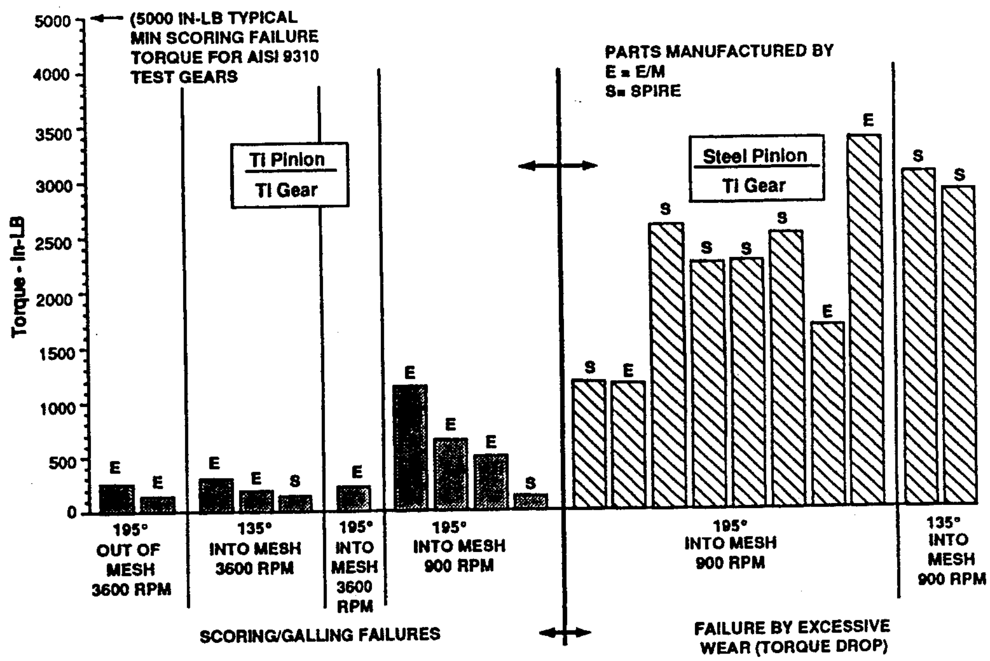


Figure 20. Surface modified Titanium gear scoring test results.

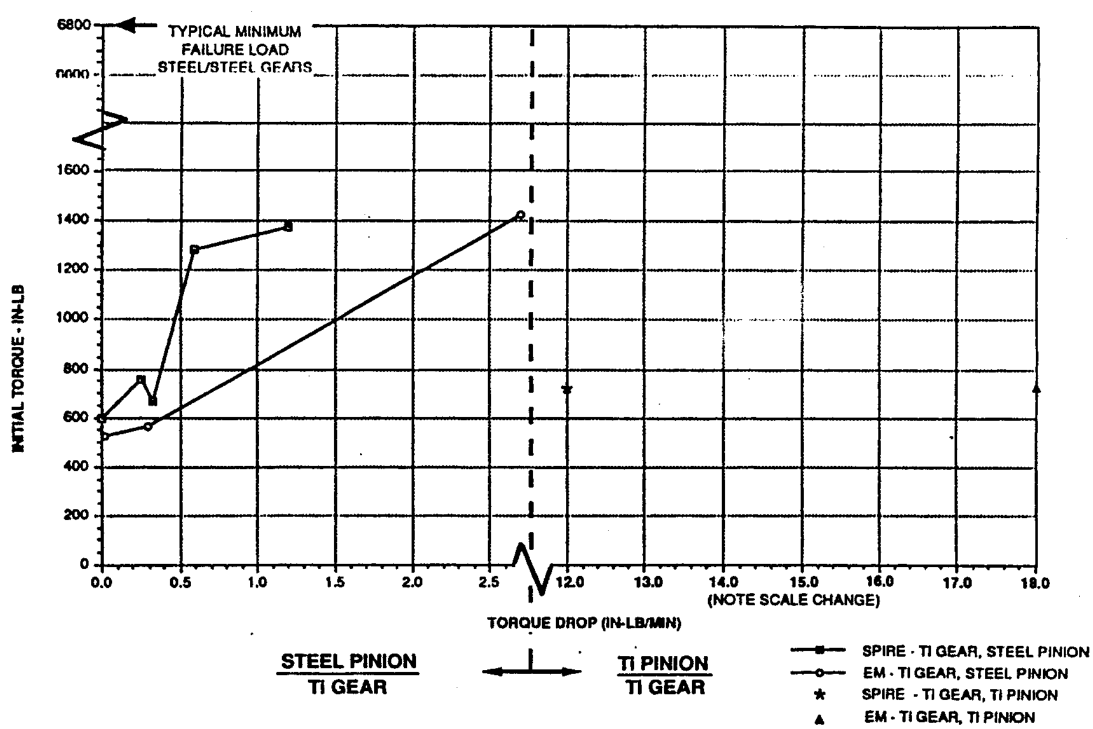


Figure 21. Surface modified Titanium gear surface durability test results.